15. Heat Pipes in Electronics (1)

15.1 Components of a Heat Pipe

The three basic components of a heat pipe are:

15.1.1 The Container

The function of the container is to isolate the working fluid from the outside environment. It has to therefore be leak-proof, maintain the pressure differential across its walls, and enable transfer of heat to take place from and into the working fluid.

15.1.2 The Working Fluid

A first consideration in the identification of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirements are:

- compatibility with wick and wall materials
- good thermal stability
- wettability of wick and wall materials
- vapor pressure not too high or low over the operating temperature range
- high latent heat
- high thermal conductivity
- low liquid and vapor viscosities
- high surface tension
- acceptable freezing or pour point

The selection of the working fluid must also be based on thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the heat pipe like, viscous, sonic, capillary, entrainment and nucleate boiling levels.

In heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force. In addition to high surface tension, it is necessary for the working fluid to wet the wick and the container material i.e. contact angle should be zero or very small. The vapor pressure over the operating temperature range must be sufficiently great to avoid high vapor velocities, which tend to setup large temperature gradient and cause flow instabilities.

A high latent heat of vaporization is desirable in order to transfer large amounts of heat with minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. The thermal conductivity of the working fluid should preferably be high in order to minimize the radial temperature gradient and to reduce the possibility of nucleate boiling at the wick or wall surface. The resistance to fluid flow will be minimized by choosing fluids with low values of vapor and liquid viscosities.

15.1.3 The Wick or Capillary Structure

It is a porous structure made of materials like steel, aluminum, nickel or copper in various ranges of pore sizes. The prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. It must also be able to distribute the liquid around the evaporator section to any area where heat is likely to be received by the heat pipe. Often these two functions require wicks of different forms. The selection of the wick for a heat pipe depends on many factors, several of

which are closely linked to the properties of the working fluid.
The maximum capillary head generated by a wick increases with decrease in pore size. The wick permeability increases with increasing pore size. Another feature of the wick, which must be optimized, is its thickness. The heat transport capability of the heat pipe is raised by increasing the wick thickness. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick. Other necessary properties of the wick are compatibility with the working fluid and wettability.

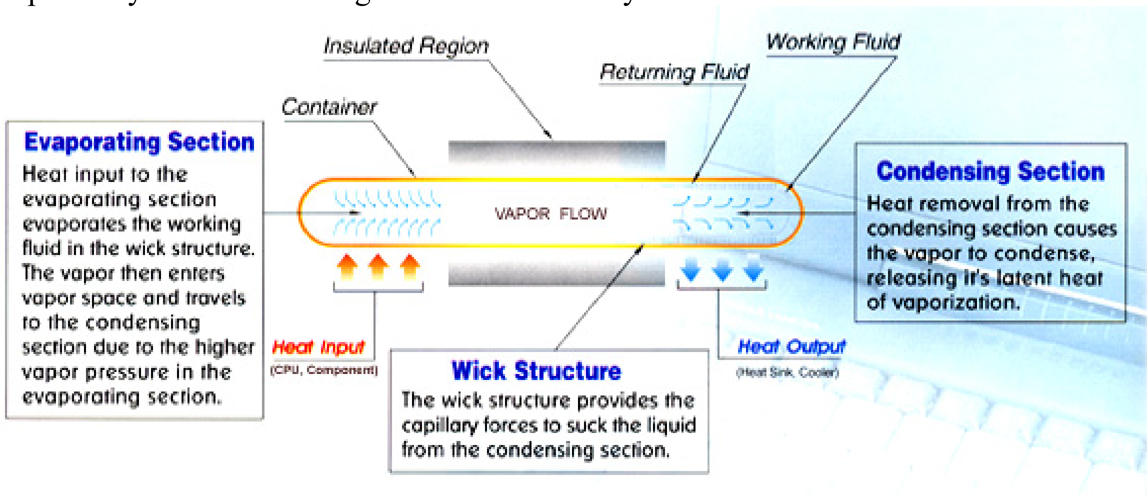

Figure 15.1 Components of the heat pipe

Figure15.2 Wick structures

15.2 Principle of Operation

As shown in Figure15.3, the heat pipe in its simplest configuration is a closed, evacuated cylindrical vessel with the internal walls lined with a capillary structure or wick that is saturated with a working fluid. Since the heat pipe is evacuated and then charged with the working fluid prior to being sealed, the internal pressure is set by the vapor pressure of the fluid.
As the heat input to the evaporator, liquid in the wick structure is vaporized, creating a pressure gradient in the vapor core. Such pressure gradient forces the vapor to flow along the pipe to the cooling region where it condenses releasing its latent heat of evaporation, which is rejected to the surrounding by a heat sink.
The liquid then returns to the evaporator region through the pores in the wick structure by the action of capillary pressure produced by the small pores of the wick structure. As a result, heat is absorbed at one end of the heat pipe and rejected to the other. The working fluid serves as the heat transport medium. The heat input region of the heat pipe is called evaporator, the cooling region is called condenser, and this is because the working fluid is being vaporized or condensed. In between the evaporator and condenser regions, there may be an adiabatic region.

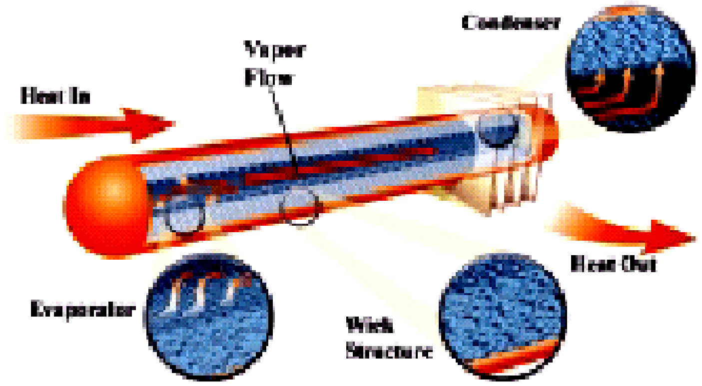

Figure 15.3 Principle of operation of heat pipe

15.3 The Special Features of Heat Pipes

The heat pipe has its special features:

15.3.1 Very High Thermal Conductivity

Heat pipe utilizes latent heat of evaporation of the working fluid to transfer heat from the evaporator to condenser of the heat pipe. This mode results a very high thermal conductivity. The effective thermal conductivity is several orders of magnitudes greater than that of the best solid conductor. Figure 15.4 shows the comparison of the effective thermal conductivity of heat pipe with that of solid copper and solid aluminum rods. The length and diameter of the three devices are, respectively, equal to 0.5m and 1.27cm. The rate of heat flow from one end to another of the devices was 20 W. The temperature differences for the three devices are indicated in Figure 15.4 for copper and aluminum rods, the temperature differences are 260 ^{o}C and 400 ^{o}C, respectively. However, the temperature difference for heat pipe is only 6 ^{o}C. This indicates that the effective thermal conductivity of the heat pipe is about 43 times larger than that of copper and 66 times larger than that of aluminum.

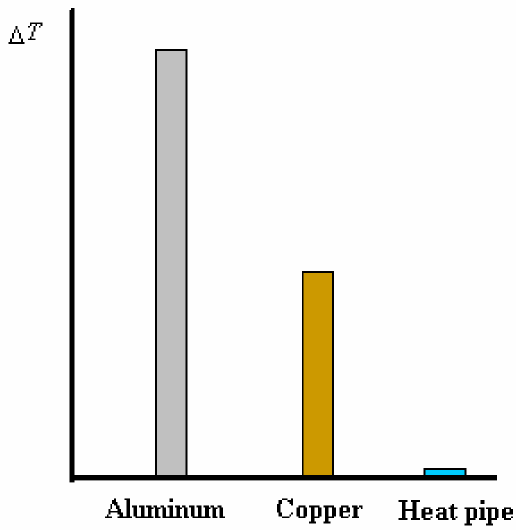

Figure 15.4 Comparison of the devices temperature difference "effective thermal Conductivity"

15.3.2 Low Relative Weight

The heat pipe is not a solid metal piece**.** The weight can be significantly reduced. In the previous example, it was found that the weight of the solid copper and solid aluminum rods are about 13.7 and 4.2 times greater than that of the copper-water heat pipe.

15.3.3 Reliable in Operation

Heat pipes do not have moving parts; they are extremely reliable. The main cause of failure is non-condensable gas generation in the heat pipe. By proper chosen of container and working fluid combination, this problem can be eliminated.

15.3.4 Flexible

The heat pipes can be made in various forms. Circular heat pipe is the most popular from, since it is easy fabrication and low cost. There exist flat plate and double casing heat pipes, rigid and flexible heat pipes, as well as large and micro heat pipes.

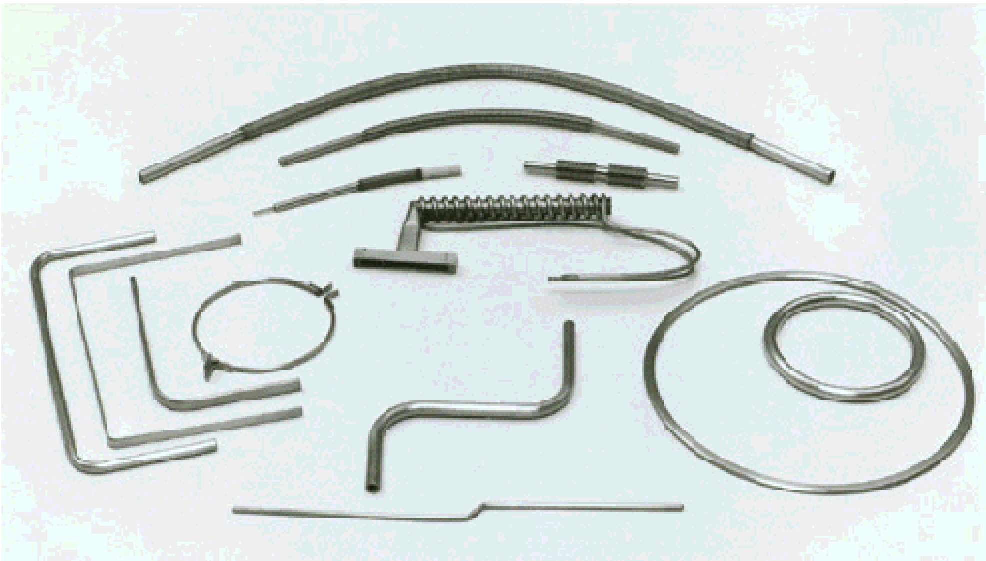

Figure 15.5 Various forms of flexible heat pipes

15.3.5 The Temperature Operating Range

Heat pipe can be designed to operate over a wide range of temperature from cryogenic applications using helium or nitrogen as the working fluid to high temperature applications using silver. The type of working fluid and the operating pressure inside the heat pipe depend on the operating temperature. The operating temperature, in general, should be above the triple point temperature and below the critical temperature of the working fluid. For example the triple point and the critical of water are, respectively, 0.01 ^{o}C and 374.1 ^{o}C. This is the reason that the recommended working temperature of water heat pipe is set between the two temperatures, as shown in Table 15.1. One more factor should be considered is high saturation pressure at high operating temperature. For high saturation pressure, the thickness of the container must be large. This will result a large transverse thermal resistance due to large conduction thermal resistance across the container walls. In electronic cooling applications it is desirable to maintain junction temperature below 80 to 150 ^{o}C, copper-water heat pipe are typically used. Table 15.1 shows the range of working temperature for some working fluids.

Table 15.1 shows the range of working temperature for some working fluids

Fluids	**Temperature Range ^oC**
Helium	-271 ---- -269
Nitrogen	-203 ---- -160
Ammonia	-78 ---- 100
Acetone	0 ---- 120
Methanol	10 ---- 130
Water	30 ---- 200
Mercury	250 ---- 650
Sodium	600 ---- 1200
Silver	1800 ---- 2300

15.4 The Limitation of Operation with Heat Pipe

The maximum heat transport capacity of a heat pipe is governed by five primary heat transport limitations, which must be addressed when designing a heat pipe as a function of the heat pipe operating temperature. These heat transport limits include: viscous, sonic, capillary pumping, entrainment or flooding, and boiling. Each heat transport limitation is summarized in Table 15.2 with description and its cause and suggested solution.

Table 15.2 Heat transportation limitation and its potential solution

Heat Transport Limitation	Description	Cause	Potential Solution
Viscous	Viscous forces prevent vapor flow in the heat pipe	Heat pipe operating below recommended operating temperature	Increase heat pipe operating temperature or find alternative working fluid
Sonic	Vapor flow reaches sonic velocity when exiting heat pipe evaporator resulting in a constant heat pipe transport power and large temperature gradients	Power/temperature combination, too much power at low operating temperature	This is typically only a problem at start-up. The heat pipe will carry a set power and the large ^T will self correct as the heat pipe warms up
Entrainment (Flooding)	High velocity vapor flow prevents condensate from returning to evaporator	Heat pipe operating above designed power input or at too low an operating temperature	Increase vapor space diameter or operating temperature
Capillary	Sum of gravitational, liquid and vapor flow pressure drops exceed the capillary pumping head of the heat pipe wick structure	Heat pipe input power exceeds the design heat transport capacity of the heat pipe	Modify heat pipe wick structure design or reduce power input
Boiling	Film boiling in heat pipe evaporator typically initiates at 5-10 W/cm^2 for screen wicks and 20-30 W/cm^2 for powder metal wicks	High radial heat flux causes film boiling resulting in heat pipe dry out and large thermal resistances	Use a wick with a higher heat flux capacity or spread out the heat load

15.5 Applications of Heat Pipe for Cooling of Electronic Systems

Heat pipe heat sink has been frequently used to remove the heat from power transistors, Thyristors, and individual chips. Currently, a popular application to use heat pipes is cooling Intel's Pentium processors in notebook computers.
Perhaps the best way to demonstrate the heat pipes application to electronics cooling is to present a few of the more common examples.

1- Cooling of Laptop Computer

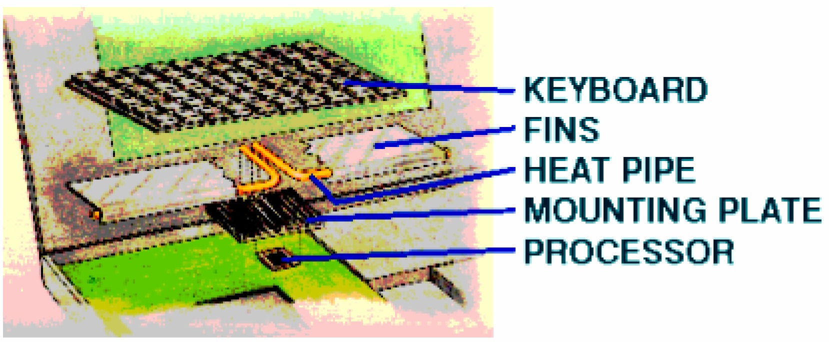

Figure 15.6 Heat pipe technology used in a laptop computer

2- Cooling of High Power Electronics

In addition, other high power electronics including Silicon Controlled Rectifiers (SCR's), Insulated Gate Bipolar Transistors (IGBT's) and Thyristors, often utilize heat pipe heat sinks. Heat pipe heat sinks similar to the one shown in Figure 15.7, are capable of cooling several devices with total heat loads up to 5 kW. These heat sinks are also available in electrically isolated versions where the fin stack can be at ground potential with the evaporator operating at the device potentials of up to 10 kV. Typical thermal resistances for the high power heat sinks range from 0.05 to 0.1°C/watt. Again, the resistance is predominately controlled by the available fin volume and air flow.

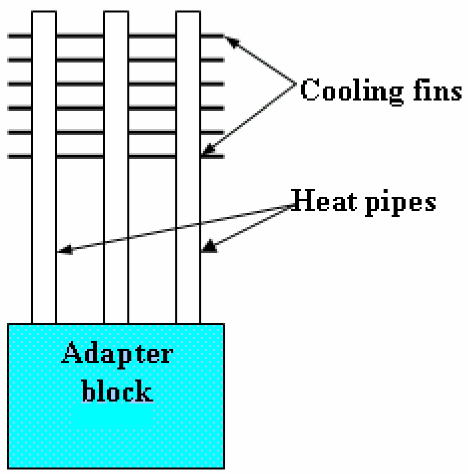

Figure 15.7 High power heat pipe heat sink assembly

Figure 15.8 Heat pipe heat sink cools four IGBT's used as motor controllers in heavy industry

Figure 15.9 shows a large heat pipe unit that has several IGBTs mounted on it. The IGBTs are attached to a mounting plate and heat pipes embedded in the plate transports the heat to an air-cooled fin section. There are several different sized units like this being used in the field. Heat rejection from units like these is from 500 W to 8.3 kW with thermal resistance values from 0.004^{o}C/W to 0.062^{o}C/W. another example of some multi-kilowatt heat pipe units installed in a motor drive cabinet as shown in Figure 15.10.

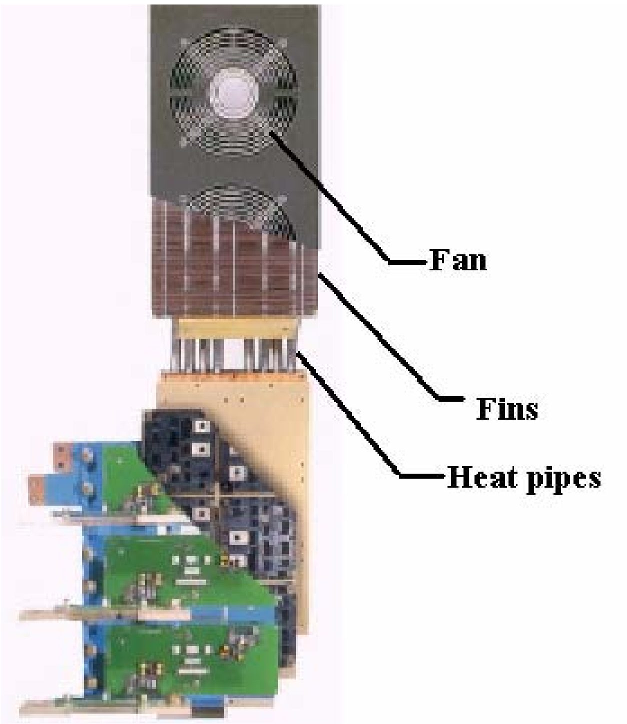

Figure 15.9 Multi-Kilowatt heat pipe assembly

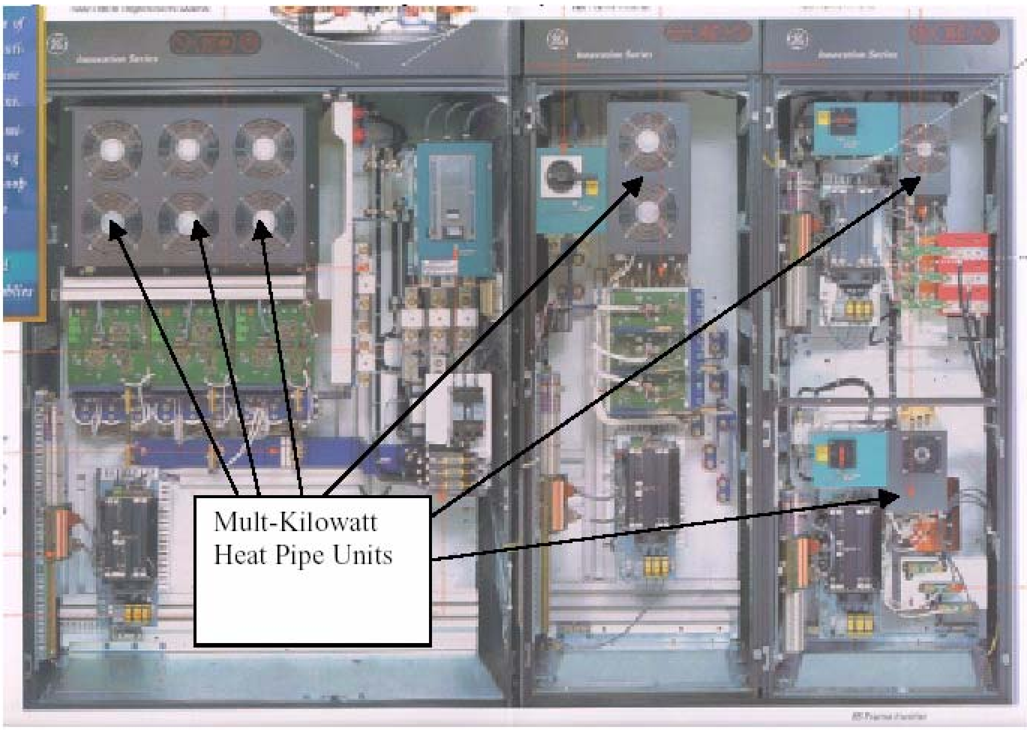

Figure 15.10 Multi-Kilowatt heat pipe units mounted in a motor drive cabinet

15.6 Heat Pipe Performance

Heat pipe performance is a function of the size of the evaporator and condenser areas, wick construction, fluid media and pipe orientation.

The operating temperature and energy transfer performance of a heat pipe is a function of its working fluid. Fluids that have a high latent heat of vaporization λ, high surface tension σ and a low viscosity are considered viable candidates. The relative performance of a fluid in terms of its ability to optimize flow can be assessed using the relation ship

$$\Pr ormance\ \ (Pf) = \frac{\lambda\,\sigma}{\nu}$$

Table 15.3 Characteristics of a few common fluids

Property	Ammonia	Water	Freon 21	Sulfur Dioxide	Mercury
Operating Range (°F)	−50 to 125	40 to 450	−20 to 200	15 to 110	400 to 820
Surface Tension σ, lb/ft	0.00124	0.005	0.00062	0.001	0.0322
Heat of Vaporization λ, BTU/lb	508.	980.	62	149	128
Kinematic Viscosity ν, ft^2/hr	0.014	0.038	0.0076	0.011	0.00414
Performance Factor p_f, $\frac{\text{BTU hr}}{\text{ft}^3}$	45.	129.	5.	13.	996.

The energy transferred at the evaporator in terms of the wick flow rate $\dot{m}_{wick}$ is

$$Q_{evap} = \lambda\,\dot{m}_{wick}$$

The flow rate depends upon the cross-sectional wick area and porosity in addition to the density and capillary diffusion rate of the fluid. Porosity also influences pipe performance at different orientations. A variety of wick structures may be used, including screen or woven wire meshes, sintered powders extruded grooves along the inside length of the pipe wall. Designs that increase the flow rate experience an attendant increased capability for thermal energy transfer.

15.7 Case Studies

- Show the effect of fluid media on heat pipe performance.
- Show the effect of orientation of heat pipe on its performance.